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Teardown Index: Impact of property values on carbon dioxide emissions of single family housing in Vancouver

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ABSTRACT

Buildings are significant drivers of climate change, generating one third of global greenhouse gas emissions. When new buildings are constructed to high performance standards, increased rates of building replacement spurred by rising property values can raise the operating efficiency of building stocks. However, it can take years before the embodied greenhouse gas emissions associated with new construction are offset by more efficient operations. This paper calculates the carbon dioxide emission payback period of newly constructed efficient single family homes in Vancouver, British Columbia. The average carbon dioxide emission payback period of 168 years for a typical high efficiency new home renders it unlikely that emission savings will be realized before it is replaced. A statistical model called the Teardown Index is presented, which indicates that replacing older poorly performing homes with new high efficiency homes in Vancouver will result in 1.3–2.8 million tonnes of additional carbon dioxide equivalent emissions between 2017 and 2050. For each percent increase to the compound annual growth rate of property values, an additional 150 thousand tonnes of CO_2e will be released between 2017-2050. The findings suggest that current policies aimed at reducing emissions through new high efficiency buildings should be reconsidered.

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1. Background and context

Carbon dioxide (CO_2) emissions are significant drivers of climate change, which constitutes an intensifying threat to human and natural systems [32]. Buildings generate one third of global greenhouse gas (GHG) emissions [17,29,44,61], and consume approximately 30% of secondary energy. GHG emissions from buildings have more than doubled since 1970, and are projected to double or triple by 2050 [30]. Reducing CO_2 emissions of buildings will be a key component to meeting the Intergovernmental Panel on Climate Change (IPCC) recommendations, which call for reduction of CO_2 emissions by a factor of 4 to prevent irreversible changes to climate [31].

1.1. Operating and embodied impacts

Buildings cause environmental impacts at every stage of their lifecyle, from construction to operation and maintenance, to decommissioning at end-of-life [13]. *Operating impacts* refer to environmental impacts produced by basic building operations, such as heating and cooling, lighting, appliances and equipment, and plug loads. *Embodied impacts* refer to the environmental impacts associated with constructing the buildings themselves. Embodied impacts include upstream effects associated with producing construction materials, such as extracting raw materials, processing, and manufacturing, as well as the impacts of the construction itself, which include transporting materials to site and assembling them. Finally, embodied impacts include maintenance or replacement of components during the useful life of the building, as well as decommissioning, disassembly, and recycling or disposal at end of life [48].

Quantifying operating and embodied impacts requires a consistent methodology to ensure accurate assessments and comparisons. Methods for measuring the embodied impacts of buildings have been reviewed by many authors [1,14,21,40,60] and can be broadly categorized into (1) input-output, (2) process and (3) hybrid-based analysis. In addition, Life Cycle Assessment (LCA), which is a leading internationally accepted method that can be used to compare the environmental impacts of similar products or services [33], is becoming more commonplace. LCA has been employed to compare the cumulative operating and embodied im-

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pacts of buildings on the environment during all lifecycle stages, from product, construction, use, end-of-life and beyond [12,45].

Although LCA is governed by ISO standards, comparisons across studies can be complicated due to a lack of agreement about system boundaries, such as whether to measure primary versus secondary energy, or account for indirect as well as direct effects of resource use [10,20,27,28,37]. Also, Pomponi and Moncaster [45] demonstrate that the duration investigated in LCAs varies, with 90% of the LCAs covering less than 60% of a building's life cycle stages. Often little data is available on use and end-of-life stages. The same study also demonstrates a lack of consistency in LCAs arising from malleable boundary conditions [39] and varied assumptions which yield strong variation in results and prevent effective benchmarking. Haapio and Viitaniemi's [23] analysis of 17 environmental assessment tools concludes that comparisons between different LCAs are "difficult, if not impossible" due to variations in building types or lifecycle stages between studies, and a general lack of methodological transparency. Despite these challenges, LCA studies of buildings can provide useful approximations of the impacts of buildings on the environment, particularly as regards the relationship of operating to embodied impacts. A survey of more than 73 residential and commercial building LCAs indicates that operating impacts typically account for between 75% and 90% of environmental effects over a lifecycle of 50 years for conventional construction [13,46].

1.2. Interrelation of operating, embodied, and total impacts

Current policies aimed at reducing the environmental impacts of buildings in North America and Europe have focused exclusively on operating impacts [19], in keeping with their dominant contribution to overall impacts. However, focusing exclusively on operating impacts remains at best an incomplete strategy, which fails to acknowledge the interrelationships between operating and embodied impacts. For example, a common method of reducing operating energy is to increase insulation, which adds to embodied impacts [52]. Embodied impacts can reach up to 60% of total impacts in high efficiency houses [16,52,56]. As building operations become more efficient, reducing the total impacts of buildings will require a thorough understanding of the relationship of operating to embodied impacts.

1.3. Emission payback period

The relationship between operating and embodied impacts can be understood in terms of its *payback period*, a term borrowed from finance that refers to the length of time required to recover the cost of an initial investment. We use the term "emission payback period" to refer to the length of time required for the reductions to operating CO_2e emissions to equal the initial "investment" of embodied CO_2e emissions released during upgrades required to produce the efficiencies. The emission payback period is a function of the amount of embodied CO_2e emissions released, the consequent reductions to operating CO_2e emissions, and the service life of new building or renovation. For example, Verbeeck and Hens [64] examine the effects that upgrading building envelopes have energy consumption of Belgian buildings, finding that the embodied energy investments of certain energy efficiency measures (such as adding insulation) are paid back by reduced energy consumption in under three years. Once the initial investment of embodied CO_2e emissions are recovered, the measure begins producing actual reductions to overall CO_2e emissions. The CO_2e emission payback period can also illustrate the ineffectiveness of certain measures. For instance, Huang et al. demonstrate that shading devices on a particular Hong Kong building facade have a minimal effect on energy consumption and never achieve payback, adding to CO_2e emissions over the life of the building, rather than reducing them [26]. A growing body of literature attests to the importance of assessing the emission payback period of environmental impact mitigation strategies [30], which make it possible to assess the viability and effectiveness of potential environmental impact mitigation strategies.

1.4. Case: Vancouver, BC

We use the emission payback period to assess the environmental effects of recent development of single family homes (SFHs) in Vancouver, Canada. Between 2005 and 2017, residential property prices in Vancouver increased by 261%, with a 28% price increase in the last three years alone [47]. Increasing numbers of older SFH are torn town and replaced in response to this dramatic rise in property values, which has produced Canada's most expensive real estate [25], as owners seek to maximize property values in areas where nearly all available lots are already built out. The majority of older Vancouver homes are uninsulated wood frame construction. Between 1985 and 2017, 26,800 SFH, or 40% of all SFHs in residentially (RS) zoned areas, were demolished and replaced with new SFH [4,9]. BC Assessment standards dictate that when 65% or more of a home is replaced, it is considered new construction, whereas less than 65% is considered a renovation. During the period of 2005–2011, 97% of all permitted construction activity in BC was above the 65% standard; only 3% of construction activity consisted of renovations, or 206 of 6521 permits issued [4]. The data shows that complete teardown and replacement of existing SFH is currently the dominant approach in the Vancouver context.

Replacing older building stock with newer buildings constructed to higher efficiency standards in Vancouver is often defended by local authorities on the grounds that it reduces operating emissions. However, numerous studies that have shown renovation is also an effective strategy for reducing operating emissions [38,50]. It is generally (though not always) true that new buildings built to higher energy standards reduce operating emissions. In the case of RS-zoned areas of Vancouver, new SFH must meet aggressive efficiency performance standard that restrict the CO_2e emissions of new homes to 12 $kgCO_2e/m^2$/year, from the 2007 baseline of 23 $kgCO_2e/m^2$/year [62]. This represents nearly a 50% gain in efficiency, which is substantial, although a study has shown that such gains could also be realized through renovation [41]. When embodied emissions from the new construction are considered, the environmental case for total replacement becomes even less clear. What is the overall effect of teardown and replacement on total emissions for SFH in Vancouver? Answering this question requires calculating the emission payback period for the structures in question, at the scale of the individual building lot and the city as a whole.

2. Research contribution

This paper presents a method for assessing total CO_2e emissions resulting from SFHs in Vancouver, at the scale of a single lot and the entire city. Both operating and embodied impacts are included, and the payback period required to offset embodied impacts through reductions to operating impacts is calculated. At the scale of the lot, the research (1) compares the typical average environmental impact of a new SFH against the existing SFH it replaces, by calculating the emission payback period and comparing it to the operating impacts of the original structure. Because RS-zoned areas of Vancouver consist of a single building type, these areas offer a unique opportunity to compare the overall environmental outcomes produced by current practices. At the scale of the city, the research (2) establishes a relationship between rising real estate values and changes to the replacement rate of SFHs in

Vancouver. Finally, by applying the environmental impacts established in (1) to the correlation of real estate values with replacement rates in (2) enables us to (3) assess the impact of changing land values on the total CO_2e emissions of the city's SFH stock.

The research is motivated by a desire to create a method capable of establishing the total impacts of buildings that accounts for embodied as well as operating impacts. The methods presented enable a more accurate assessment of impacts and outcomes associated with replacing older buildings with newer more efficient structures, as well as the time required to realize any projected savings. The methods will enable more informed decisions about whether it is environmentally favourable to encourage renovation versus outright replacement of existing buildings. Sound policy-making must rest on accurate information. The research will be of value to municipalities seeking evidence-based environmental policies to meet building emissions targets currently in place and, ultimately, to strengthen climate change mitigation efforts.

3. Materials and methods

Assessing the environmental impacts corresponding to different rates of replacement of existing single family homes requires three elements: (1) a method for establishing operating and embodied CO_2e emissions of new and existing SFH building stock; (2) a method for establishing the period of time, referred to as the "emission payback period" required to recover the CO_2e emissions released to build the new, more efficient building and (3) a model capable of predicting how many SFH will be replaced, to enable projected outcomes into the future at the scale of the city.

Although operating and embodied impacts include impacts on human health, ecosystem quality, natural resource use, and climate change and others, for the sake of simplicity, the study employs global warming potential (GWP), expressed in CO_2 equivalents (CO_2e), to indicate the building's contribution to climate change [45]. As defined by RS zoning, SFHs refer to detached homes, which includes duplex homes and auxiliary dwelling units where they occur on the same property, but excludes low- and high-rise multi-unit residential buildings.

3.1. Overview of operating emissions

Operating CO_2e emissions from SFHs in Vancouver come from two primary sources: electricity, and natural gas, which is used primarily for space and water heating in homes where electricity is not used for those purposes. Approximately 66% of SFH energy demand in Vancouver is met by electricity,[1] of which 98% is produced from low-carbon renewable sources such as hydroelectricity [6]. Estimating operating CO_2e emissions requires establishing usage rates for electricity and natural gas, and then converting energy usage in each category to associated CO_2e emissions based on geographically-specific conversion factors. The methods of determining consumption varies according to whether the subject is existing buildings or new construction, as indicated below.

3.1.1. Operating emissions of existing buildings

Establishing the operating CO_2e emissions associated with existing SFHs of different vintages in Vancouver is difficult due to a lack of specificity about the age and location of buildings in available data sets documenting actual energy use. However, a reasonably accurate account of operating CO_2e emissions of SFH by vintage can be achieved through comparison and extrapolation of available data sets documenting consumption. Energy consumption by end use (e.g. space heating, lighting, etc.) and typical energy source (gas, electricity) for SFHs in Lower Mainland, (the region surrounding and including Vancouver), was obtained from BC Hydro and Power Authority (BC Hydro), which supplies electricity to Vancouver (Appendix A: Table A1, [66]). BC Assessment data was used to calculate the areas of SFHs in the Lower Mainland, [4], so that energy consumption data by end use and energy source could be converted to consumption per area (Appendix A: Table A2). This yielded a general picture of consumption rates across all vintages. To generate vintage-specific operating CO_2e emissions, space heating and ventilation energy requirements per m^2, which account for 48% of SFH energy demand, were adjusted using gross thermal output by vintage cohort and by building type data from Natural Resources Canada Comprehensive Energy Use Database (CEUD) [42] for SFHs across BC (Appendix A: Table A3).The CEUD database indicates that gross thermal output across Canada varies widely by building vintage, with older buildings generally consuming more thermal energy. The remaining end use categories (hot water, space cooling, appliances, lighting, electronics, and other) were held constant across vintages, as it was assumed that consumption in these categories does not vary significantly by age of the building. Finally, the average consumption of natural gas and electricity per square meter was calculated by vintage for SFH in the Lower Mainland. (Appendix A: Table A4). This secondary energy data was converted to primary energy, scaling up consumption by factors of 2.05 for electricity and 1.02 for natural gas [22] to account for the energy required to extract, process, and deliver the fuel to the building [18]. Carbon emissions associated with electricity and gas use were calculated using regionally-specific environmental impact conversion factors provided by the British Columbia Ministry of Energy [7]. As a final step, the data was cross-checked for accuracy against the Vancouver Community Energy and Emissions Inventory [8], which measures aggregate CO_2e emissions at the municipal scale, but does not differentiate by building type or age. The aggregate operating CO_2e emissions calculated were found to be within 5% of the Vancouver Community Energy and Emissions Inventory, which was deemed an acceptable variation.

The operating energy data sets considered demonstrate that operating energy consumption, and the corresponding CO_2e emissions, generally vary with building age in the Canadian context. This finding is supported by previous studies [35,54,55,57,58], which have demonstrated the viability of using building age as a predictor of energy consumption and GHG emission rates for bottom-up and archetypical analyses of multiple buildings. The operating emission rates of Vancouver SFHs by vintage (using NRCan's CEUD vintage cohorts) are summarized in Table 1 below.

3.1.2. Operating emissions of new buildings

Operating CO_2e emissions for newly built SFHs are assumed to follow guidelines established by the Zero Emissions Building Plan (ZEBP), a municipal policy first proposed in Vancouver in 2016. While the policy is still under review, it is establishes an aspirational municipal emission target that will exceed provincial requirements in British Columbia. The ZEBP mandates that SFH built from 2020 to 2025 emit at most 7 $kgCO_2e/m^2$/year, which is reduced to 0 $kgCO_2e/m^2$/year after 2025. The research assumes that SFHs built from 2017 to 2020 will emit at the same rate as SFHs built from 2011 to 2017.

3.2. Embodied emissions

Embodied CO_2e emissions can be divided in two categories: initial and recurring [28]. Initial embodied CO_2e emissions do not repeat and are predominantly concentrated in lifecycle stages preceding the use stage. Recurring embodied CO_2e emissions reflect the emissions resulting from maintaining, repairing and replacing

[1] Eddie Young (Policy Advisor, BC Hydro), e-mail correspondence with Joseph Dahmen, Vancouver, British Columbia, 26 June 2017.

Table 1
Vancouver SFH primary operating CO_2e rates and area metrics by vintage.

Vintage [3–5]	Operating carbon emissions ($kgCO_2e/m^2$/year)	Number of SFH [3–5]	SFH Internal floor area [3–5] (m^2)	Average lot area (m^2)	Average unused buildable area (m^2)
Prior to 1946	**15.42**	20,147	266	499	108
1946–1960	**14.17**	10,606	220	499	154
1961–1977	**12.43**	9,014	259	467	91
1978–1983	**11.00**	3,180	304	432	20
1984–1995	**9.78**	11,909	411	502	−34[a]
1996–2000	**8.74**	3,227	357	487	8
2001–2005	**8.56**	3,447	316	475	40
2006–2010	**7.99**	2,938	368	493	1
2011–2017	**7.74**	3,468	392	520	−2

[a] Negative values indicate that SFHs have interior areas which are greater than that permitted under the current zoning policy floor space ratio.

building components that have shorter lifespans than the overall building itself.

3.2.1. Embodied emissions of existing SFHs in Vancouver

Replacing existing SFHs with new buildings produces embodied CO_2e emissions that would not otherwise be incurred due to new construction. Embodied CO_2e emissions are thus calculated for new construction, whereas the embodied CO_2e emissions of existing SFHs are considered to be a "sunk costs" and are not calculated, as they do not affect the CO_2e emission payback period. There is one exception, however. Recurring embodied CO_2e emissions have been applied to existing SFH. Verbeeck and Hens [63] establish that embodied CO_2e emissions increase with building age due to recurring embodied CO_2e emissions. An LCA of a residential building in Australia by Treolar et al. [59] indicates that recurring embodied energy added 32% to the initial embodied energy outlay after 30 years, while the LCA by Zhang et al. [67] of a wood framed SFH in Vancouver revealed that 33% of the total embodied CO_2e emissions over the 60 year lifespan of the building were attributed to recurring embodied carbon, representing an annualized rate of 1 $kgCO_2e/m^2$/year. Thus a rate of 1 $kgCO_2e/m^2$/year of recurring embodied CO_2e emissions has attributed to existing SFHs in Vancouver.

3.2.2. Embodied emissions of new SFHs in Vancouver

New SFH construction in Vancouver typically consists of three story light wood platform framing on a concrete foundation. 48 LCAs of North American residential buildings under 465 m^2 between 1 and 6 stories were reviewed from an embodied CO_2e benchmark study by Simonen et al. [53], in addition to 3 LCAs of Canadian wood frame residential structures [43,51,67] and 2 Passivhaus LCAs [11,15]. LCAs which did not directly account for Stage A (cradle through construction) as well as those with outlying embodied CO_2e emissions above 1000 $kgCO_2e/m^2$ or below 100 $kgCO_2e/m^2$ were removed from the data set provided by Simonen et al. The average embodied CO_2e emissions during Stage A for the 34 remaining LCAs is 232 $kgCO_2e/m^2$ (see Appendix B: Table B1). An LCA by Dahlstrom et al. [15] comparing a SFH built to conventional versus PassiveHouse standards finds that the building to PassiveHouse standards results in an increase embodied CO_2e emissions from 216 $kgCO_2e/m^2$ to 251 $kgCO_2e/m^2$, or 16%. Because the ZEBP energy and CO_2e emission guidelines accord with or surpass PassiveHouse standards, the 232 $kgCO_2e/m^2$ average for North American residential construction was increased by 16% to account for the additional embodied CO_2e impacts of building to a higher standard. This yields a benchmark initial embodied CO_2e emission rate for new SFH in Vancouver at 269 $kgCO_2e/m^2$. This figure lies within the range of 201 $kgCO_2e/m^2$, the median value of the 53 LCAs North American residential buildings under 6 storeys and less than 465m^2 filtered from a review of Simonen et al. [53], and 400 $kgCO_2e/m^2$, determined by Salazar and Meil's [51] LCA of a high-efficiency wood-framed SFH in Canada. To the initial embodied CO_2e of new SFHs was added 1 $kgCO_2e/m^2$/year in recurring embodied CO_2e emissions, mimicking that applied to existing SFHs.

Finally, it could be argued that the embodied CO_2e emissions of demolition should be counted toward the overall embodied CO_2e emissions of new SFHs, because these emissions are released as a result of the new construction. However, embodied CO_2e emissions of the demolition of existing SFH have been omitted from the study due to a lack of reliable data. This omission was deemed acceptable, as numerous studies find that demolition accounts for less than 2% of overall embodied impacts [13,34,43,46,65,67].

3.3. Total Emissions, building longevity and payback periods

Once operating and embodied CO_2e emissions are determined, it is possible to calculate the total CO_2e emissions. Total CO_2e emissions are the sum of operating emissions and embodied emissions, expressed as CO_2e. The total CO_2e emissions of a newly constructed SFH are evaluated against the operating emissions of the older SFH it replaces, using a payback period calculation. The payback period represents the number of years required for the annual operating CO_2e emissions of the existing SFH to equal the total CO_2e emissions of the new construction. The payback period calculation is expressed in Eq. (1) (SFH payback period formula):

$$Y = \frac{ECi''}{\left(ECr'' + OC''\right) - \left(ECr' - OC'\right)} \quad (1)$$

(Y) Payback period; ($'$) replaced SFH; ($''$) replacing SFH; (EC) embodied CO_2e emissions; (OC) operating CO_2e emissions; (i) initial; (r) recurring.

Replacing an existing building with a new building that reduces operating CO_2e emissions results in a positive CO_2e payback period, measured in years. The payback period is negative if new building has higher operating emissions than the building it replaces. Finally, in the event that an existing building is replaced by a new building with the same operating CO_2e emissions, results in a division by zero. This mathematical exception occurs because the payback period is effectively infinite in this case: the embodied emissions are not paid back because no additional efficiencies are introduced.

The payback period is the relative yardstick by which emission savings or debt of new SFHs can be measured, as compared to a control state that consists of the operating emissions and recurring embodied emissions of the original building. If a replacement SFH is younger than its payback period, the total emissions of that lot exceed the emissions that would have been incurred had the SFH been left in place (CO_2e debt). If the new SFH is older than its payback period, the total emissions of the lot are lower than the

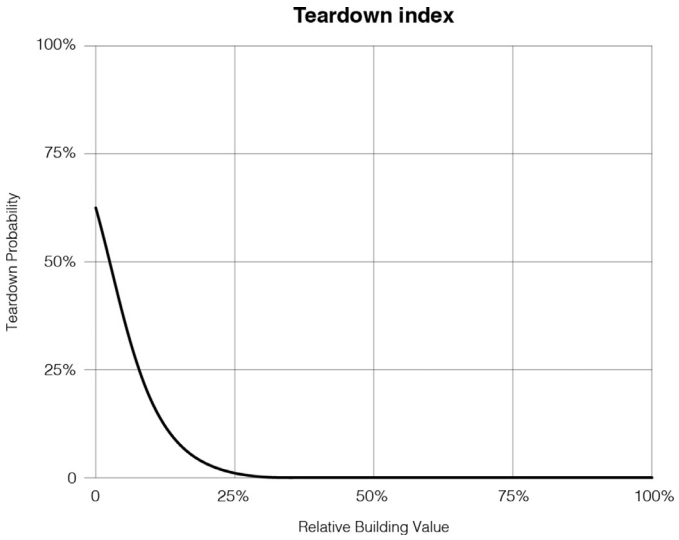

Fig. 1. Teardown Index graph.

emissions of the original SFH (CO_2e savings). Since operating CO_2e rates vary by SFH vintage cohort, and replacement SFHs maximize their allowable buildable square footage per lot, payback periods will vary by vintage, as well as by any potential increase in size of new construction.

3.3.1. Teardown Index

It is necessary to estimate the life expectancy of the new construction to assess whether replacing different vintages of SFH with more efficient buildings is beneficial. If the payback period exceeds life expectancy, efficiency gains are unlikely to be realized. To assess the duration of life of SFH in Vancouver, a data visualization tool called the Teardown Index was developed to model the probability that a SFH will be replaced. Historic land transfer data and land value assessments from BC Assessment were used to identify the determinants of SFH teardown/rebuilds within RS zoning [3–5]. All but 1.3% of historic teardowns of SFH could be associated with the property being transacted (bought or sold). Rosenthal et al. [49] developed a land and building value assessment model that concludes that the *relative building value* is the most important determinant of a transacted property getting torn down, which refers to the quotient of the assessed building value to the total value of the property. Building on this earlier work, we fit a logistic model to the historical data based on relative building value that predicts the teardown or survival of transacted buildings with 82% accuracy (Fig. 1). The modelled probability of a transacted SFH with relative building value x to be torn down is given by Eq. (2) (Teardown Index formula):

$$P(x) = \frac{1}{1 + e^{-(0.53-20.23x)}} \quad (2)$$

The accuracy of the model was not significantly improved by adding variables like lot area or total building value, nor by using more sophisticated models. This work relied on BC Assessment's valuations of land and buildings, which we found to be an unbiased estimator of building values, although at times with high variance on individual buildings. The teardown probability never exceeds 63%, even when an existing buildin is valued at zero, which indicates that speculation on future land value gains is an important factor in some of these transactions.

3.3.2. Projecting total emissions of Vancouver's SFH stock to 2050

Correlating the predictions with emission payback periods for different vintages of SFHs makes it possible to estimate the total CO_2e emissions of different scenarios at the scale of the city. Six scenarios are modeled to study their effect on total CO_2e emissions of SFH in Vancouver from 2017 to 2050. The first scenario is a control, which is defined by no change in property prices and an artificial mechanism whereby no SFHs are replaced, resulting in emissions produced entirely by building operation, with no new embodied emissions. The remaining scenarios project the evolution of the SFH stock to 2050 using average price compound annual growth rates (CAGR) between from −2% to 8.24%. The growth rates of 2.23%, 5.08%, and 8.24% correspond to the CAGR of SFHs prices in Vancouver over the last 1, 5 and 3 years respectively. The −2% CAGR scenario is added to provide insight into the likely effect of a loss of value on replacement rates. The effect these different scenarios produce on total CO_2e emissions are presented below.

3.4. Assumptions and limitations

The research focuses on CO_2e emissions as the most closely linked to global warming. In relying on past LCAs to determine embodied CO_2e emissions, the research inherits their scenario and model uncertainties [37]. Moreover, many other types of environmental impacts are associated with the construction, maintenance, operation and replacement of SFHs, such as ozone depletion, respiratory inorganics, human toxicity, ionising radiation, ecotoxicity, ozone formation, acidification, terrestrial eutrophication, land use, waste and resource consumption. When these are considered, it is likely that the impacts could increase unevenly between operating and embodied impacts. In addition, the scope of the study is limited to CO_2e emissions directly associated to SFHs. Indirect emissions associated with infrastructural requirements of SFHs, such as roads and parking are not considered, nor are the indirect emissions due to transportation, or from consumption-related emissions [36]. Emissions are considered on a per area basis, which does not account for the number of people served by spaces, and as such may be a less accurate method of accounting for emissions than a per capita basis. It is likely that replacing SFHs with denser forms of inhabitation, such as mid-rise, ground oriented development, would have a profound effect on CO_2e emissions per capita.

It could be argued that the decision to replace SFHs is typically made by individual owners on economic grounds, a view corroborated by the relative building value used to calculate the probability of replacement. Nevertheless, the city has the means to incentivize other forms of development, such as renovation or equipment upgrades, instead of total replacement.

Projecting SFH total CO_2e emissions to 2050 requires making assumptions about current policy, while disregarding the possibility of potentially significant policy changes. The Zero Emissions Building Plan is used to determine future consumption, despite uncertainty about its prospects for approval and anticipated enforcement and compliance. The projections also assume that the current distribution of energy sources will be maintained into the future. Gas produces over 16 times more CO_2e than hydroelectricity per unit of energy, and heating accounts for 62% of SFH energy demand. If homeowners move toward replacing natural gas with electric heat pumps for space and water heating in the future, the projections would overstate operating CO_2e emission rates, while underestimating CO_2e emission payback periods.

4. Results

4.1. Emission payback periods by SFH vintage

Average CO_2e payback period by SFH vintage cohort calculations are summarized in Table 2. Because operating emission rates of existing SFHs increase with age, new SFH homes that replace older SFH demonstrate shorter payback periods. For example, a

Table 2
Replacement SFH CO_2e payback periods by vintage.

Vintage	Payback period of SFH built from 2020 to 2025 (years)	Payback period of SFH built after 2025 (years)
Before 1946	73.1	25.2
1946–1960	291.3	34.0
1961–1977	138.6	30.1
1978–1983	82.6	26.2
1984–1995	71.8	25.0
1996–2000	176.3	31.6
2001–2005	548.4	35.9
2006–2010	277.5	33.8
2011–2017	343.9	34.6

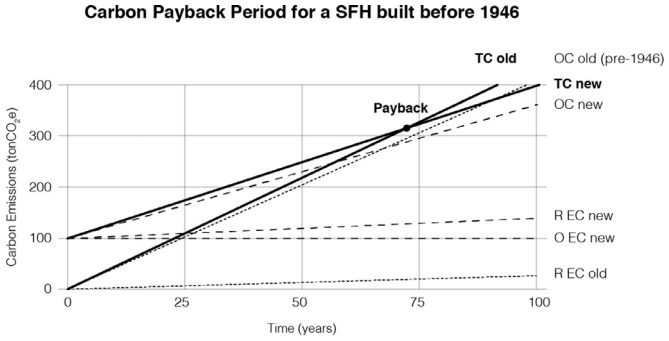

Fig. 2. CO_2e payback period for a new SFH replacing pre-1946 SFH.

new SFH replacing a SFH built prior to 1946 has a payback period of 73 years (Fig. 2), if constructed between 2020 and 2025, and 25 years if built after 2025, when emissions standards are tightened for new construction. In contrast, replacing an average SFH built after 2011 has a CO_2e payback period of 344 years, which is reduced to 34.6 years if built after 2025. For all SFHs in Vancouver, the weighted average CO_2e payback period is 168 years, which drops to 29 years for SFH built between 2020 and 2025 and those built after 2025, when operating emissions effectively drop to zero.

4.2. Scenarios of real estate appreciation

Table 3 summarizes the CO_2e emissions from Vancouver SFHs for different real estate price compound annual growth rates (CAGR). In the control scenario, where no SFHs are replaced and the current stock of SFHs is conserved, the total CO_2e emissions released by operating and maintaining these homes between 2017 and 2050 amounts to 8.9 M $mtCO_2e$.

For an SFH price CAGR of 2.23% over the same time period, an estimated 32,366 SFHs will be demolished and replaced. Exploiting maximum FSR buildable area during rebuilding will add 3.2 M m^2 of interior space to those structures. From 2017 to 2050, the total emissions from this scenario will amount to 10.9 M $mtCO_2e$, which

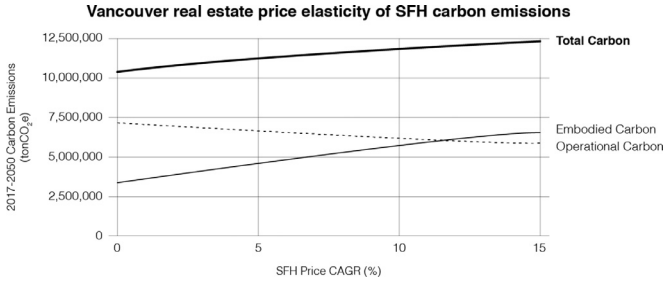

Fig. 3. Real estate price elasticity of SFH CO_2e emissions.

represent an increase of 1.9 M $mtCO_2e$ emissions when compared to the control scenario mentioned above.

At a CAGR of 5.08%, 39,929 SFHs will be replaced, and 3.3 M m^2 of interior space will be added to the housing stock, causing total emissions from 2017 to 2050 to reach 11.3 M $mtCO_2e$—a 26.5% increase from the control scenario.

In the extreme growth scenario, based on the 8.24% CAGR rise recorded in SFH prices from 2015 to 2017, 47,276 SFH being replaced between 2017 and 2050, resulting in a net increase of 3,390,215 m^2 of interior space, and 11.7 M $mtCO_2e$ of total emissions—a 31.8% increase over the control scenario.

Notably, the model shows that for a CAGR of −2%, 21,921 SFH will be replaced, producing 10.2 M $mtCO_2e$ emissions. A 2% reduction in property value does not affect the relative building values significantly enough to cause a major change in replacement rates.

4.3. The real estate price elasticity of SFH CO_2e emissions

Elasticity refers to the responsiveness of one variable to a change in another. Generated by the median value of 100 Teardown Index simulations, the real estate price elasticity SFH CO_2e emissions is presented in Fig. 3. This curve represents the change in total, operating and embodied CO_2e emissions from the total stock of SFHs over the 2017–2050 period given a change in the CAGR of SFH land values over that period. For each percentage point increase in CAGR land value price gains, an additional estimated 150 thousand tonnes of CO_2e are added between 2017 and 2050.

5. Discussion

The results show that at the scale of both the individual building lot and the city, the environmental benefits of tearing down and replacing even very poorly performing buildings are dubious at best in Vancouver. The average CO_2e payback period of 168 years for a typical home built to current standards renders it unlikely that emission savings will be realized before the structure is replaced. Even the shortest CO_2e emission payback time of 71 years for new SFH constructed to current energy consumption requirements may easily exceed the life of the home in the current eco-

Table 3
Total CO_2e emissions by scenario, 2017-2050.

Scenario	Real estate CAGR (%)	SFH replaced	Net increase of SFH stock internal area (m^2)	Total carbon emissions (metric tonnes of CO_2e)
1	Moratorium	0	0	8,913,000
2	−2%	21,921	2,627,278	10,214,801
3	0%	26,183	2,836,140	10,441,025
4	2.23%	32,366	3,178,000	10,856,000
5	5.08%	39,929	3,262,000	11,275,000
6	8.24%	47,276	3,390,000	11,744,000

nomic climate, in which buildings are torn down and replaced at a frenetic pace. Increasingly stringent energy consumption requirements that reduce the allowable amount of operating energy after 2025 to zero bring down the payback period significantly, although the CO_2e emission payback period ranges between 25 and 36 years even under the zero operating consumption scenario. It is as yet uncertain whether these aspirational guidelines will be achieved on the proposed schedule.

At the scale of the city, the long payback times documented give rise to large CO_2e emission debts for all of the real estate growth scenarios considered. For all of the scenarios considered, replacing existing SFH with more efficient buildings causes a significant net increase in CO_2e emissions for the period between 2017 and 2050. It is especially notable that the increases to overall emissions occur despite 50% reductions to operating emissions, which can be considered very significant. This finding can be considered conservative in terms of the environmental effects of replacement. Carbon emissions associated with the demolition of existing SFHs were not considered, which would add to the CO_2e emissions of new constructions. More significantly, only CO_2e emissions were considered, among the many impacts of building construction. It is likely that the overall impacts of new construction would increase considerably when impacts to human health, ecosystem and water quality, and resource use are considered.

It should be noted that the findings are geographically specific to Vancouver, a city with ample sources of renewable energy, and a mild climate, both of which drive down operating emissions considerably. A major aspect contributing to the long payback times reported are the low rates of operating CO_2e emissions due to renewable sources of electricity in Vancouver. The natural gas that makes up the remainder of operating energy demand has emission factors that are low when compared to other sources of fossil energy, such as coal or oil. In localities where operating energy demand is met by more carbon-intensive fuel sources, or a more severe climate, CO_2e payback periods would diminish considerably, favouring building replacement. Likewise, were these energy sources to change in the future (from hydro electricity to generation from the combustion of fossil fuels, for example), the payback times would be affected. The longer payback times due to reduced operating emissions are exacerbated by the sources of embodied emissions. Unlike the low carbon sources of operating energy in Vancouver, most construction materials are still manufactured with conventional energy sources, and are less responsive to geographical location due to the global distribution networks that characterize contemporary construction. Changing patterns of primary energy use directly will directly impact the results of the study.

5.1. Future directions

The role of embodied impacts will increase relative to total impacts in the future, as operating energy efficiency gains are realized across the stock of SFH in Vancouver. This will make it even more essential to account for embodied CO_2e emission metrics in future policy. Moving forward, strengthening access to LCA data for building components and processes, such as a localized Environmental Product Declarations database, establishing clear accounting practices, [2,17] and mandating institutional oversight are likely prerequisites to that end. Such measures could facilitate the introduction of embodied CO_2e emission accounting in the design phase of construction [24] at the scale of the SFH, rather than on an ad hoc post-occupancy basis as is currently the case.

The results also point to the relevance of renovating poorly performing existing structures, as opposed to completly replacing them. Mohammadpourkarbasi and Sharples [41] note that bringing two Victorian houses in the UK to near Passive-House standards results in a 75% reduction in operating emissions, with a CO_2e payback period of 6 years. Ma et al. [38] and Rysanek and Choudhary [50] note that renovation can be an effective method of increasing the sustainability of buildings, but that complex factors influence adoption. In the case of Vancouver, where older single family homes typically consist of light wood framing on insufficient foundations, extensive renovation often approaches outright replacement. However, even in this context, renovations to building systems, such as replacement of gas-fired heating equipment with electric heat pumps powered by renewable hydroelectricity, would address the consumption of natural gas, which is largest source of CO_2e emissions. Slowing the replacement rate of SFHs, discouraging the outright replacement of SFHs through taxation, zoning, or other policy mechanisms, and promoting retrofitting, each have the capacity to decrease the total CO_2e emissions of Vancouver's SFH stock while minimizing disruptions to current architectural heritage, density patterns and urban form.

6. Conclusion

Buildings emit up to a third of CO_2e emissions globally. Most emission mitigation strategies to date have focused on reducing operating impacts due to their large share of overall impacts. However, as the proportion of embodied impacts increases due to operational efficiencies, accounting for embodied impacts is imperative. Embodied impacts can be understood in the context of CO_2e emission payback period, which refers to the period of time required for operational savings to recover the amount of embodied CO_2e emitted by constructing a new building. This study uses CO_2e payback periods to assess total CO_2e emissions for the stock of single family houses in Vancouver Canada in the context of the city's plan to reduce the CO_2e emissions of building by 80% by 2050. The amount of time for the total emissions of replacement SFHs to equal those of replaced SFHs, range from 73 to 548 years for SFHs built to 2020 efficiency standards, and 25 to 36 years for SFHs built to 2025 efficiency standards. A statistical tool called the Teardown Index was used to project future demolition and replacement of single family homes in Vancouver. Four scenarios of real estate capital appreciation growth rates were investigated, ranging between 0% and 8.24% CAGR. Generally, higher rates of real estate growth translate to higher rates of demolition and replacement. Each percentage point increase in annual land value price gains corresponds to an additional 150 thousand tonnes of CO_2e released between 2017 and 2050 as a result of operating and embodied impacts. Despite significant operating efficiency increases, replacing existing buildings with new efficient buildings will emit between 1.3–2.8 and million tonnes of additional CO_2e emissions. These findings suggest that replacing older buildings with high efficiency buildings in Vancouver is not an effective strategy to achieve municipal CO_2e emission mitigation goals when all impacts are considered.

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Appendix A: Operating impacts

Table A1
Average energy requirements by end use and fuel source per SDH per year for 2014 in Lower Mainland, BC [66].

Fuel	Gas (kWh)	Gas (GJ)	Gas %	Electric (kWh)	Electric (GJ)	Electric %	Total (kWh)	Total (GJ)	Total %
Space heating	8132.6	29.3	81.44%	1853	6.7	18.56%	9985.6	35.95	44.66%
Hot water	2380.0	8.6	77.78%	680	2.4	22.22%	3060.0	11.02	13.68%
Space cooling	0.0	0.0	0.00%	78	0.3	100.00%	78.0	0.28	0.35%
Appliances	0.0	0.0	0.00%	3244	11.7	100.00%	3244.0	11.68	14.51%
Lighting	0.0	0.0	0.00%	1871	6.7	100.00%	1871.0	6.74	8.37%
Electronics	0.0	0.0	0.00%	1784	6.4	100.00%	1784.0	6.42	7.98%
Other	0.0	0.0	0.00%	1460	5.3	100.00%	1460.0	5.26	6.53%
Ventilation	0.0	0.0	0.00%	879	3.2	100.00%	879.0	3.16	3.93%
Total	**10,512.6**	**37.8**	–	**11,849**	**42.7**	–	**22,361.6**	**80.50**	**100.00%**
% of total energy	**47.01%**	**47.01%**	**47.01%**	**52.99%**	**52.99%**	**52.99%**	**100.00%**	**100.00%**	**100.00%**

Table A2
Average energy requirements by end use and fuel source per SDH m^2/year for 2014 in Lower Mainland, BC [66].

Fuel	Gas (kWh/m^2)	Gas (GJ/m^2)	Gas % of use	Electric (kWh/m^2)	Electric (GJ/m^2)	Electric % of use	Total (kWh/m^2)	Total (GJ/m^2)	Use % of total
Space heating	36.825	0.133	81.44%	8.390	0.030	18.56%	45.215	0.163	44.66%
Hot water	10.777	0.039	77.78%	3.079	0.011	22.22%	13.856	0.050	13.68%
Space cooling	0.000	0.000	0.00%	0.353	0.001	100.00%	0.353	0.001	0.35%
Appliances	0.000	0.000	0.00%	14.689	0.053	100.00%	14.689	0.053	14.51%
Lighting	0.000	0.000	0.00%	8.472	0.030	100.00%	8.472	0.030	8.37%
Electronics	0.000	0.000	0.00%	8.078	0.029	100.00%	8.078	0.029	7.98%
Other	0.000	0.000	0.00%	6.611	0.024	100.00%	6.611	0.024	6.53%
Ventilation	0.000	0.000	0.00%	3.980	0.014	100.00%	3.980	0.014	3.93%
Total	**47.60**	**0.17**	**–**	**53.65**	**0.19**	**–**	**101.25**	**0.36**	**100.00%**
% of total	**47.01%**	**47.01%**	**47.01%**	**52.99%**	**52.99%**	**52.99%**	**100.00%**	**100.00%**	**100.00%**

Table A3
Vintage adjusted space heating and ventilation energy requirement.

Vintage	Total single detached floor space (in BC, million m^2)	Gross output thermal requirements for single detached in BC (GJ/household)	Gross output thermal requirements for single detached in BC (GJ/m^2)	Gross output therm. req. weighted average by m^2 per vintage (GJ/m^2)	Gross thermal output delta from weighted average	Vintage adjusted space heating and ventilation energy requirement (GJ/m^2)
Before 1946	8.17	80.20	0.57	–	67.54%	**0.297**
1946–1960	9.97	76.38	0.51	–	50.79%	**0.267**
1961–1977	34.16	70.59	0.43	–	27.67%	**0.226**
1978–1983	23.59	66.89	0.37	–	8.52%	**0.192**
1984–1995	44.77	59.09	0.31	–	−7.75%	**0.163**
1996–2000	16.73	49.33	0.27	–	−21.59%	**0.139**
2001–2005	15.56	51.20	0.26	–	−23.94%	**0.135**
2006–2010	20.48	49.31	0.23	–	−31.55%	**0.121**
2011–2014	13.65	50.12	0.22	–	−34.97%	**0.115**
Average	–	–	–	–	–	–
Total	**187.08**	–	–	**0.339**	–	–
Source	*NRCan CEUD 2014: Table 19*	*NRCan CEUD 2014: Table 32*	*NRCan CEUD 2014: Table 33*	*derived*	*derived*	*derived*

Appendix B: Embodied impacts

Table B1

Table A4
Primary operating CO_2e emissions per m^2 of Lower Mainland SFH adjusted by vintage.

Vintage	Space heating + ventilation: total (GJ/m^2)	Space heating + ventilation: gas (GJ/m^2)	Space Heating + ventilation: electricity (GJ/m^2)	Water heating: total (GJ/m^2)	Water heating: gas (GJ/m^2)	Water heating: electricity (GJ/m^2)	Appliances: total - all Elec (GJ/M^2)	Lighting: total - All Elec. (GJ/M^2)	Space cooling: total - All Elec (GJ/M^2)	Electricity total (GJ/m^2)	Gas total (GJ/m^2)	Electricity converted to primary in GJ	Gas converted to primary in GJ	Prim. elec in $kgCO_2e$	Prim. gas in $kgCO_2e$	Total prim. operating energy ($kgCO_2e/m^2$/year)
Before 1946	0.297	0.242	0.055	0.050	0.039	0.011	0.106	0.030	0.001	0.204	0.280	0.418	0.286	**1.238**	**14.183**	**15.42**
1946–1960	0.267	0.217	0.050	0.050	0.039	0.011	0.106	0.030	0.001	0.198	0.256	0.406	0.261	**1.204**	**12.961**	**14.17**
1961–1977	0.226	0.184	0.042	0.050	0.039	0.011	0.106	0.030	0.001	0.191	0.223	0.391	0.227	**1.158**	**11.275**	**12.43**
1978–1983	0.192	0.157	0.036	0.050	0.039	0.011	0.106	0.030	0.001	0.184	0.195	0.378	0.199	**1.120**	**9.878**	**11.00**
1984–1995	0.163	0.133	0.030	0.050	0.039	0.011	0.106	0.030	0.001	0.179	0.172	0.367	0.175	**1.087**	**8.691**	**9.78**
1996–2000	0.139	0.113	0.026	0.050	0.039	0.011	0.106	0.030	0.001	0.174	0.152	0.357	0.155	1.060	7.681	**8.74**
2001–2005	0.135	0.110	0.025	0.050	0.039	0.011	0.106	0.030	0.001	0.174	0.148	0.356	0.151	1.055	7.510	**8.56**
2006–2010	0.121	0.099	0.022	0.050	0.039	0.011	0.106	0.030	0.001	0.171	0.138	0.351	0.140	1.040	6.955	**7.99**
2011–2014	0.115	0.094	0.021	0.050	0.039	0.011	0.106	0.030	0.001	0.170	0.133	0.348	0.135	1.033	6.705	**7.74**
Average	0.177	0.144	0.033	0.050	0.039	0.011	0.106	0.030	0.001	0.181	0.183	0.372	0.187	1.103	9.256	10.36
Total	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**–**

Table B1
Data extracted from Simonen et al.

BLDG_PUB	BLDG_TYP + BLDG_US	BLDG_LOC	BLDG_NEW	$BLDG_AREA_M2	$BLDG_AREA_FT2	BLDG_$	BLDG_ST	LCA_YEAR	LCA_RE	LCA_SOUR	LCA_STAG	LCA_BLDG	LCA_MAT_Q	EC_WB_EX	**EC_LCAA_PERM2**
A05	Residentia single-fam	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2004			A	SFEI	Y	46,826,000	**244.31**
A05	Residentia single-fam	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2004			A	SFEI	Y	37,047,000	**193.29**
A05	Residentia single-fam	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2004			A	SFEI	Y	28,004,000	**139.93**
A05	Residentia single-fam	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2004			A	SFEI	Y	21,367,000	**106.77**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	40	**266.67**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	28.4	**258.18**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	25.8	**258**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	38.4	**256**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	43.1	**253.53**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	27.6	**250.91**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	39.7	**248.13**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	39.3	**245.63**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	45.6	**240**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	30.7	**236.15**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	23.3	**233**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	25.6	**232.73**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	34.4	**229.33**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	24.8	**225.45**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	29.2	**224.62**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	35.6	**222.5**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	34.9	**218.13**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	27.6	**212.31**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	42	**210**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	22.5	**204.55**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	42.9	**204.29**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	26.3	**202.31**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	30.2	**201.33**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	29.8	**198.67**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	27.4	**195.71**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	31.2	**195**
A05	Residentia other	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	27.3	**182**
A05	Residentia sther	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	26.7	**178**
A05	Residentia sther	North Ame	New	94 to 465	1001 to 5000	0	1 to 6	2011	60		ABC	SEI	N	24.8	**177.14**
A05	Residentia single-fam	North Ame	New	94 to 465	1001 to 5000	0		2014	60		ABCD	SFEI	Y	184.79	**746.64**

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